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Optimization of Solar Energy System using MATLAB Tool with MPPT Technique in WSN

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Abstract: The limited energy-storage capacity of batteries in wireless sensor networks (WSNs), particularly those deployed in remote environments, poses a significant constraint on network lifetime. Energy-harvesting (EH) technologies offer a promising solution to this limitation. Among various ambient energy sources, solar energy is widely adopted due to its availability, maturity, and environmental sustainability. The primary objective of this research is to enhance the extraction of solar energy using photovoltaic (PV)-based harvesting systems integrated with maximum power point tracking (MPPT) techniques to address the restricted battery lifespan of wireless sensor nodes. This work proposes an improved solar energy-harvesting architecture that combines MPPT with fuzzy-logic control to maximize harvested power. The aim is to improve the overall efficiency of the harvesting process by optimizing key factors such as PV module characteristics, fuzzy-logic controller performance and MPPT accuracy. Several models for solar-based EH systems have been developed in prior research. To achieve optimal performance, MATLAB/Simulink (2023a) iterative simulations were conducted to evaluate switching-regulator configurations operating under both fuzzy-logic-based and perturb-and-observe (P&O) MPPT algorithms. Experimental and simulation results demonstrate that the proposed fuzzy-logic-based MPPT outperforms the conventional P&O method. The fuzzy MPPT approach achieves higher system efficiency (η_sys), delivering improved output voltage, current, and power with reduced losses. These findings confirm that fuzzy-logic-controlled MPPT provides superior performance for solar energy harvesting in wireless sensor nodes compared to traditional P&O techniques.

Introduction

Wireless (remote) Sensor Networks (WSNs) have gained significant popularity and widespread adoption across various application domains. These networks comprise sensor nodes that monitor diverse environmental conditions and transmit the collected data to a central sink for further processing (Kanaujia and Sharma, 2023; Sharma et al., 2024).

Sensor nodes in WSNs typically rely on batteries as their primary power source, which may be either refillable or non-refillable. The use of non-refillable batteries imposes inherent limitations on the operational lifespan of WSNs and can negatively impact overall network performance, presenting a critical challenge for long-term deployment. Although rechargeable batteries are preferred, replacing or recharging them in remote or inaccessible environments, where many WSN applications are situated, can be inconvenient and logistically difficult. Therefore, extending the operational lifespan of WSNs under constrained power availability remains a significant and ongoing research challenge (Akyildiz et al., 2002). Energy harvesting (EH) technologies offer a promising solution to the limitations associated with battery-powered sensor nodes by enabling the extraction of energy from the surrounding

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environment, thereby prolonging WSN lifetime. Various EH sources, such as solar, wind, vibration, radio-frequency (RF), and thermal energy, can be utilized for this purpose (Sah et al., 2020). Among these, solar energy harvesting is particularly favored due to the high-power density achievable with solar cells, which can reach up to 15 mW/cm³. This substantial energy potential makes solar power a viable and attractive option for meeting the energy demands of WSNs (Sravanthi & Conrad et al., 2008).

The following are this research article's primary contributions:

(1) A 3.3 volts recharger for solar energy using Perturb & Observation (P&O) type, tracking of maximum power (MPPT) control strategies using MATLAB (2023a).

(2) Insolation gathers 3.3 volts recharger using Fuzzy control logic (FLC) strategies using MATLAB-Simulink.

(3) Utilizing a MATLAB-Simulink comparison is done, between Perturb and Fuzzy controller-based solar energy implementation to charge a 3.3-volt battery. It is believed that the WSN node is powered by this rechargeable battery.

Maximum power point tracking (MPPT) techniques

MPPT is a control method that maximizes power extraction from a photovoltaic (PV) or energy-harvesting source (thermal, vibration, solar, or radiofrequency). MPPT continuously modifies the operating point so the harvester consistently supplies maximum power because the output power of these sources fluctuates with temperature, irradiation, load, and other factors (Katche et al., 2023).

The Need for MPPT

a) The Maximum Power Point (MPP) is a distinct peak on PV power-voltage (P–V) and current-voltage (I–V) curves.

b) The MPP is continually changing due to environmental factors such as temperature, shade, direction, and sunlight intensity.

c) Energy harvesters only produce 50–70% of their potential power in the absence of MPPT.

d) Efficiency increases significantly with MPPT (typically 90–99%).

Because nodes in Wireless Sensor Networks (WSNs) have limited energy budgets and often rely on harvested energy to survive, this is particularly crucial.

MPPT by perturbation and observation (P&O) Technique

To assess changes in photovoltaic (PV) voltage and power (P_{PV}), the P&O algorithm continuously measures the PV module's voltage (Vpv) and current (Ipv). The algorithm uses the calculated values to incrementally adjust the converter's duty cycle (D) by a specified perturbation data, either increasing or decreasing it as needed (D=0.01) (Sera et al., 2013).

In the following perturbation, the duty cycle is raised ($D = D+\Delta D$) if $\Delta PPV > 0$ and $\Delta VPV > 0$ or $\Delta PPV < 0$ and $\Delta VPV < 0$, due to a shift in the preceding perturbations' duty cycle.

In the following disturbance, the duty cycle is decreased ($D = D-\Delta D$) if $\Delta P > 0$ and $\Delta VPV < 0$ or $\Delta PPV < 0$ and $\Delta VPV > 0$, due to the shift in duty cycle during the previous disturbances.

The algorithm will keep repeating or doing this process until the maximum power is reached.

i.e., $\Delta P_{PV} = 0$ and $\Delta V_{PV} = 0$

If the duty cycle value is allowed to fluctuate at each perturbation step, the algorithm fails to satisfy the prior criterion, causing the P&O algorithm to oscillate around the MPP. The P-V slope curve is utilized in this procedure. Given that the model is operating at the MPP, the algorithm assumes the power slope and voltage curve are nearly zero.

The P&O method works by matching the load's impedance and applying the solar panel theorem. Impedance matching is necessary for optimal power transfer via the DC-DC converter. A DC-DC converter's impedance is matched by adjusting the duty cycle of its MOSFET switch. The equation for the duty cycle (D), output voltage (Vo), and input voltage (Vin) is as follows:

$V_o = V_{in}. D$

and,

$R_{in} = RL / D^2$

Consequently, the output voltage (V_o) of the solar energy harvester varies with the duty cycle (ΔD). The output voltage (V_o) rises when the duty cycle (D) increases, and vice versa.

To obtain the highest power switches to the load and for optimization, the duty cycle (D) can be adjusted to match the input solar panel impedance with the load resistance (RL).

The procedure in the P&O algorithm is given in a flow chart and MATLAB coding as shown in figure 1.

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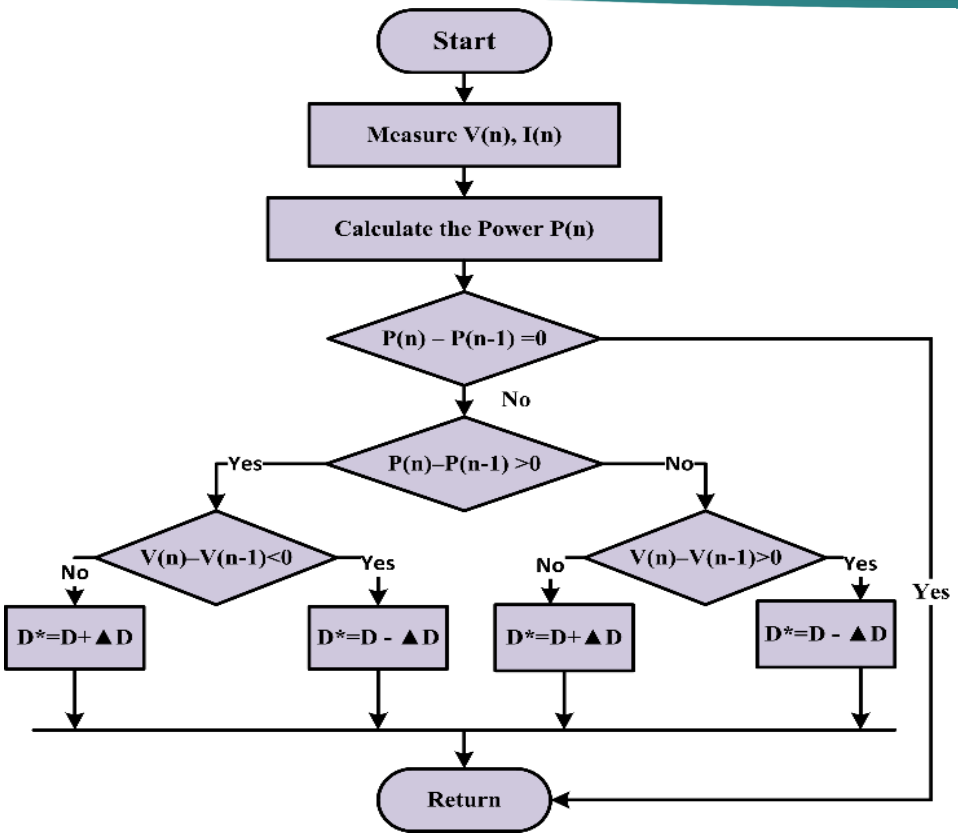

Figure 1. Flowchart of Perturb and Observe (P&O) Algorithm-based MPPT algorithm.

Algorithm1. P&O MPPT algorithm.

functionduty cycle = PAndO MPPT Converter(V_pv, I_pv, V_ref, step_size, delta)
persistentpreviouspowerprevious duty (Remoaldo et al., 2021).
ifisempty (previous power)
previouspower = 0;
end
ifisempty (previous duty)
previousduty = 0.5;
end
% Calculate power
power = Vpv .* Ipv;

% Compare current power with previous power
ifpower> previous power
delta = -delta;
end
% Update duty cycle
duty cycle = previous duty + delta;
% Clamp duty cycle within [0, 1]
duty cycle = min(max(duty cycle, 0), 1);
% Update previous power and duty cycle
previouspower = power;
previous duty = duty cycle;
end

MPPT by Fuzzy Logic Control Technique

Due to its ability to handle nonlinearity, analyze imprecise data, and function without having a precise mathematical formulation, fuzzy logic control has grown in popularity over the past ten years. The use of fuzzy logic control has been greatly expanded by the development of microcontrollers. The three primary stages of this method are fuzzification, which converts crisp inputs into fuzzy values, the inference system, which uses fuzzy rules to draw conclusions and defuzzification, which is the inverse of fuzzification (Dash et al., 2015).

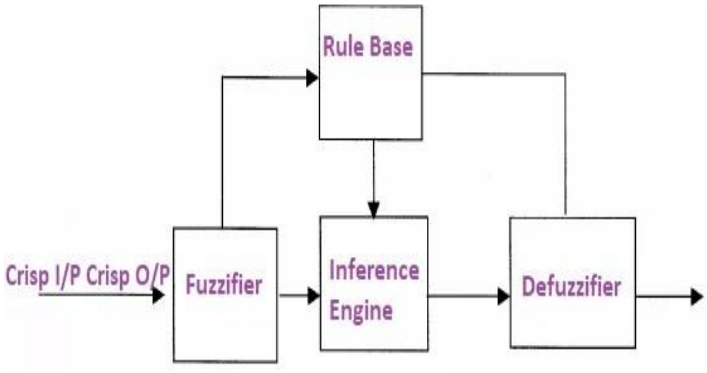

Figure 2. Diagrammatic representation of fuzzy logic control.

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Fuzzification describes the process of transforming "crisp" mathematical input into "fuzzy" semantic, changeable output, depending on membership levels in specific sets. Benchmark for Fuzzy control is generally structured in an IF-THEN format (Al Nabulsi et al., 2012; Sutikno et al., 2021).

The maximum power point of PV modules is extracted using fuzzy logic methods. Because it continuously monitors control variables such as duty cycle and voltage, this technique requires periodic updates. In solar photovoltaic systems, MPPT (Maximum Power Point Tracking) is typically employed to maximize power extraction under varying operating conditions (Priyadarshi et al., 2019). The MPPT selects the appropriate load to optimize output power. The relationship between total resistance and solar cell temperature is intricate. Both cell temperature and solar radiation intensity affect the maximum power point (MPP) of PV arrays. The tracker may stray from the MPP because of variations in light intensity, necessitating quick corrections to conserve energy. It remains difficult to track the MPP efficiently and quickly in real-world settings (Sharma and others, 2024).

A fuzzy logic approach is employed to determine the variable step size (ΔD), allowing for automatic adjustment of PV array operating points. The fuzzy logic system uses two inputs based on power variance (ΔPpv) and voltage variation (ΔVpv) to determine the changeable step size (ΔD), as depicted in Figures 2 & 3. Figure 4 illustrates the five triangular MFs that are used by both inputs and outputs: negative big (NB), negative small (NS), zero (ZE), positive big (PB), and positive small (PS). The fuzzy rule base, inspired by the P&O method, enables adaptive step-size adjustments for faster convergence. This improves tracking performance while maintaining system stability. The choice of five membership functions provides an optimal balance between precision and computational complexity, ensuring accurate MPPT control. Fewer membership functions make control coarser, while increasing the number unnecessarily increases complexity without a significant gain. This choice ensures sufficient granularity to differentiate between power and voltage variations while maintaining fast, efficient execution (Et-Torabi et al., 2025).

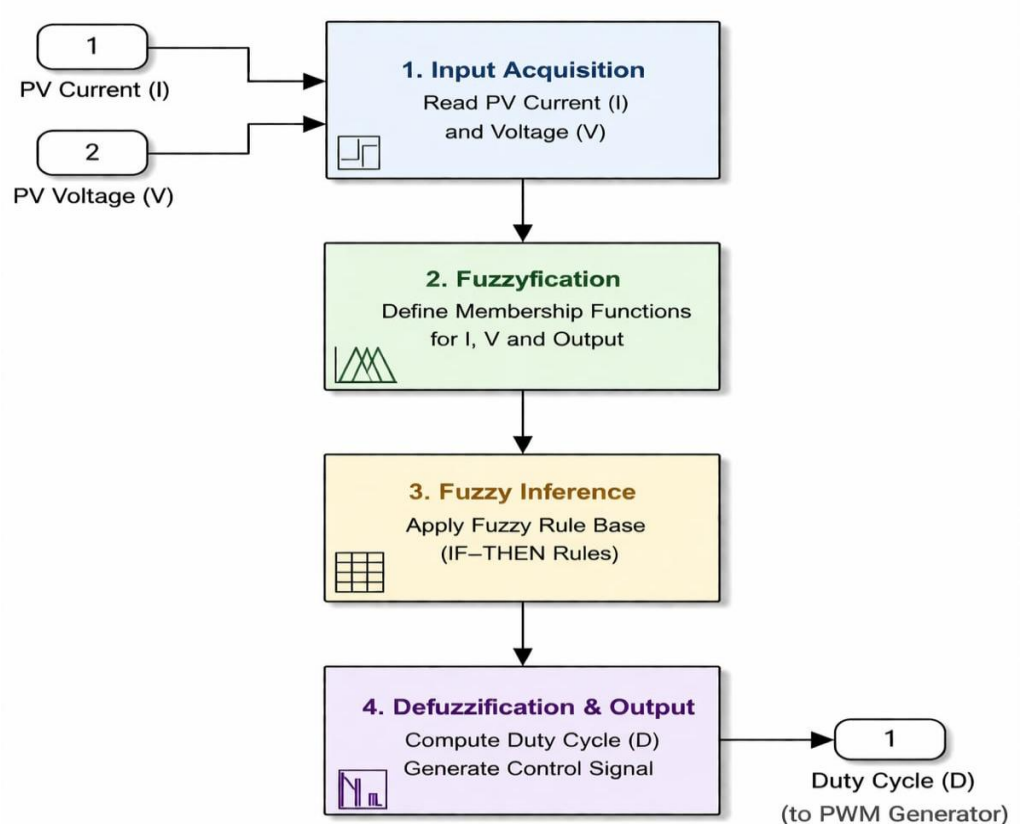

Figure 3. Proposed model for fuzzy logic algorithm.

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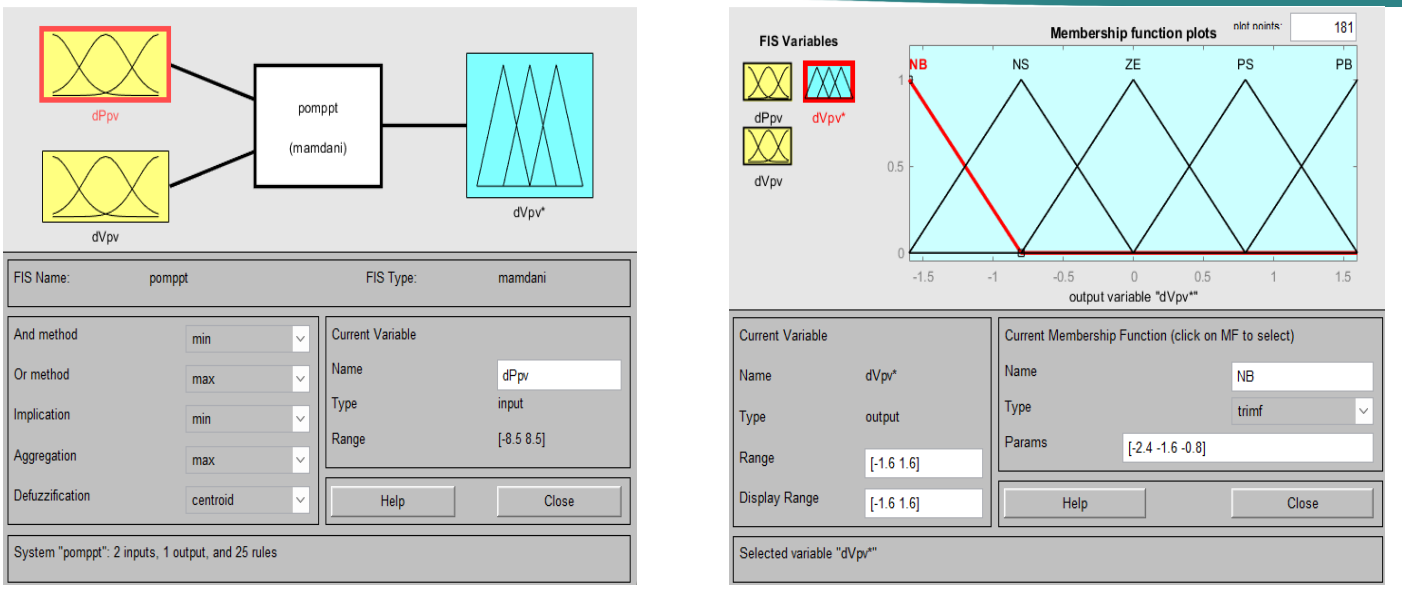

Figure 4. MATLAB diagram of the implemented FLC-based MPPT controller.

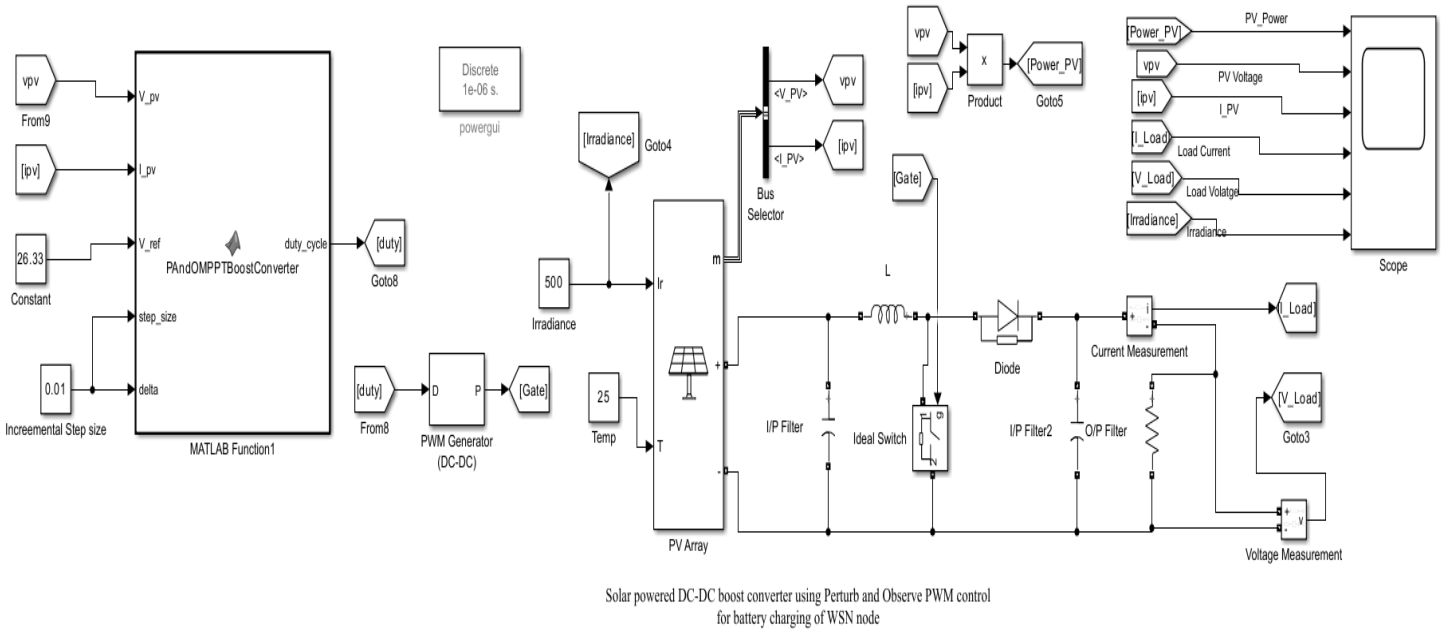

Figure 5. Simulink Model MPPT by PO system.

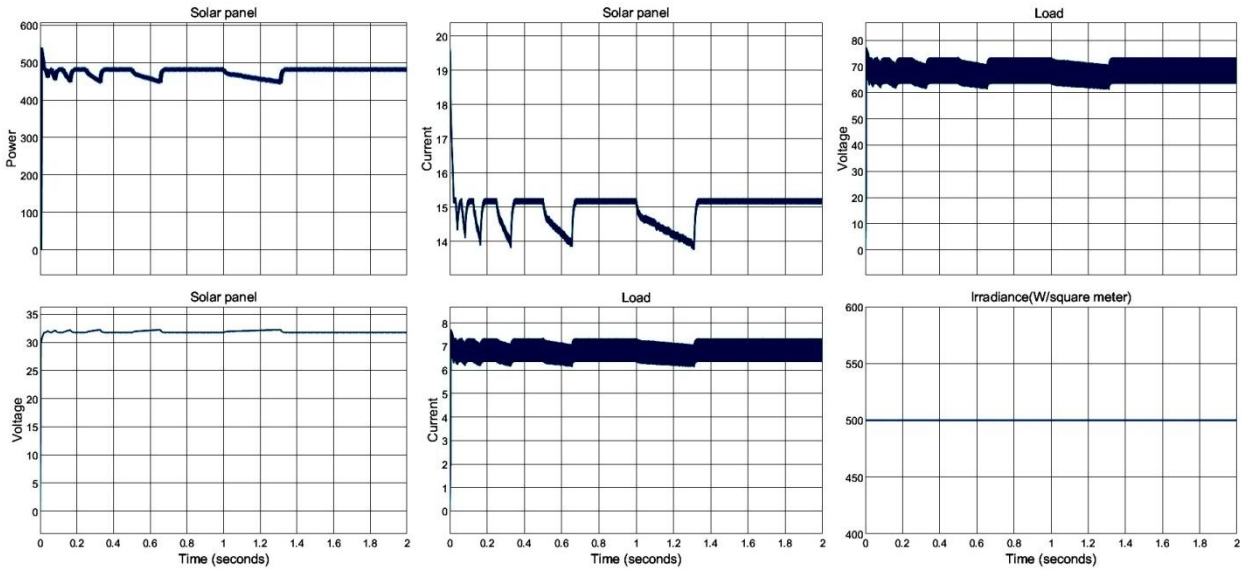

Figure 6. Simulink Results.

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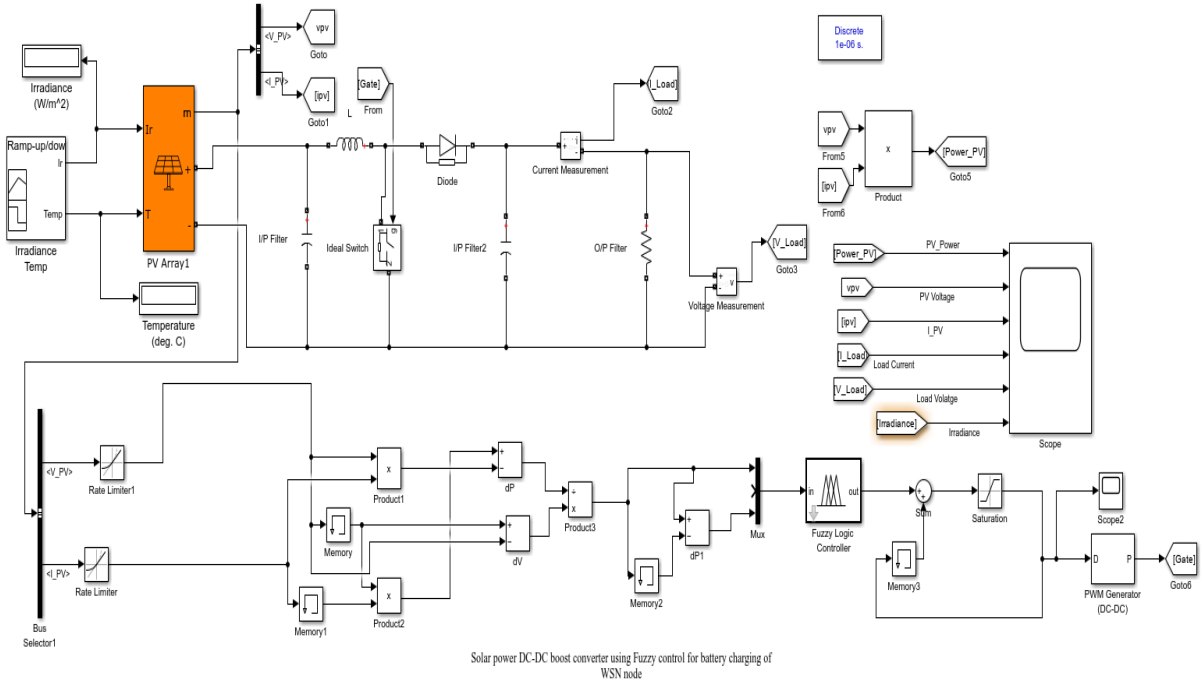

Figure 7. MPPT control Fuzzy logic with WSN battery as load.

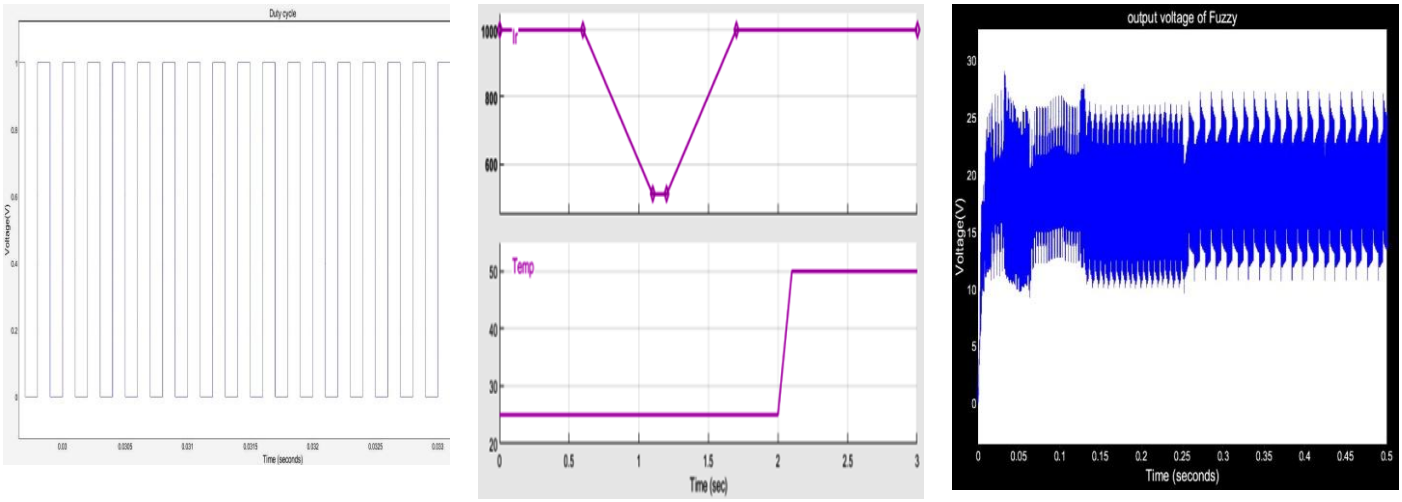

Figure 8. Simulation Results; 8(a): Duty cycle; 8(b): Irradiance & Temperature; 8(c): Output voltage of Fuzzy.

The fuzzy controller determines the changeable step size (ΔD) using two input variables. The differential voltage and differential power used by the FLC are calculated using (1) and (2).

$$\Delta(K)=P(K)-P(k-1) \quad (1)$$

$$(K)=(K)-V(k-1) \quad (2)$$

To perform inference, Mamdani's Max-Min composition method is applied. Defuzzification is executed via the center-of-gravity method, converting the fuzzy subset of the variable-step-size into real integers.

$$\Delta D = \frac{\sum_{j=1}^{n} \mu(\Delta Dj) = * \Delta Dj}{\sum_{j=1}^{n} \mu(\Delta Dj)} \quad (3)$$

Simulation experiment setup

Figure 5 shows a simulated solar-powered switching regulator with P&O logic control for battery energy storage in a WSN node, implemented in MATLAB Simulink 2023a. The MPPT control by P&O is represented by a MATLAB Simulink model in Figure 4. The solar panel receives 500 watts per square centimeter of incident solar radiation at a room temperature of 25 degrees Celsius. Only this sun energy can be converted by the solar planeinto15 mW/cm^2 at 15% efficiency.

Figure 6 shows Simulink results of MPPT control by P&O, which contain solar panel voltage, current, power and load voltage, current and irradiance. Figure 7 shows Simulink model using Fuzzy logic control with WSN battery as load. Figure 8 shows Simulation Results of 8(a)

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Duty cycle, 8(b) Irradiance & Temperature, 8(c) Output voltage of Fuzzy controller.

In Simulink, the DC-DC converter receives electrical energy from the solar cell, raising the output potential energy. Utilizing the output potential of the converter, the battery is charged. The WSN node is powered by a rechargeable battery. DC load of 100 ohms resistance, the WSN load is simulated as the output in this case. Table 2 displays the simulation parameters, including temperature, duty cycle, WSN load, solar cell current, voltage, and power, battery voltage, and irradiance.

Table 2. Simulation Parameters.

Specifications	Value in unit	Specifications	Value in unit
Irradiance (W/m2)	500Watts/m2	Temp (T)	25^0 Celsius
Capacitors (C)	100 uF	DC-DC Converter	Boost
MOSFET Switch Freq(f)	4 KHz	Max. Solar output potential (Vm)	5 v
Initial duty Cycle	0.5	Max. Solar cell output current (Im)	400 mA
Switching Voltage Loss (V_{sw})	0.3 v	Max. Power from Solar Cell(Pm)	3 watts
Inductor conduction Power Loss (PL)	50 mW	Battery Voltage	3v
MOSFET Switching Power Losses (P_{sw})	0.4 mW	Inductor (L)	200 uH
Rechargeable Battery Type	NiCd	WSN Load Model	10 Ω

Simulation results

Based on the modeling, simulation, and optimization experiments conducted for the Solar Energy Harvesting Wireless Sensor Node (SEH-WSN), it was observed that the fuzzy-logic-controller (FLC) based maximum power point tracking (MPPT) approach yields improved power-tracking performance for the photovoltaic (PV) module. Comprehensive simulation results for the FLC-based MPPT method were obtained using MATLAB/Simulink (R2023a).

The complete PV energy-harvesting system was modeled and simulated under varying solar irradiation levels to evaluate the dynamic response and efficiency of both the DC–DC converter and the fuzzy controller. Solar irradiance levels of 1100, 900, 700, 500 and 300 W/m² were applied to assess the input and output power, while the corresponding duty-cycle variations were also recorded.

Table 3 summarizes the simulation outcomes for the fuzzy-based MPPT method. The results indicate that although the MPPT controller's output power increases as irradiance decreases, the overall system efficiency decreases compared to the conventional perturb-and-observe (P&O) technique. This performance variation highlights the influence of environmental conditions on controller behavior and underscores the need for further optimization of fuzzy-based MPPT strategies under low-irradiance scenarios.

We use tracking efficiency (η) statistics to assess how well MPPT approaches operate. Typically, it is described as (Devireddy et al., 2022)-

$$\eta = \frac{\sum \mathrm{PMPPT(i)}}{\sum_{j=1}^{n} \mathrm{PMax(i)}} * 100 \qquad (4)$$

Where PMPPT: output power of the photovoltaic system using the MPPT controller, and Pmax: maximum possible output power of the PV system at MPP.

Table 3. Output of Fuzzy logic controller.

Irradiance (Watts/Sq.meter)	P_{in} (Watts)	P_{out} (Watts)	η(%)	DC
1100	268.3	260.4	98	0.75
900	219.6	211.3	96	0.72
700	166.25	158.5	95	0.61
500	110.11	102.4	92	0.53
300	58.82	54.3	92	0.47

Fuzzy control's higher efficiency results in better battery charge state, battery Current (I_B), and battery voltage (V_B) than P&O MPPT.

Limitations and Potential Enhancements for the Proposed Approach

While the proposed fuzzy logic–based MPPT controller demonstrates improved performance under varying operating conditions, several limitations and challenges remain. To further enhance controller robustness and efficiency, alternative optimization strategies may be explored:

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#Hybrid Optimization Techniques

Integrating multiple optimization algorithms—such as combining Particle Swarm Optimization (PSO) with Genetic Algorithms (GA), or Grey Wolf Optimization (GWO) with gradient-based methods—can capitalize on the complementary strengths of each technique. Such hybrid approaches have the potential to overcome the performance constraints associated with individual optimization methods and may lead to more accurate and faster MPPT convergence (Kumar et al., 2024).

#Adaptive and Self-Tuning Fuzzy Logic MPPT Controllers

Another promising direction is the development of adaptive or self-tuning fuzzy MPPT controllers that autonomously adjust their membership functions and rule sets in response to real-time environmental and operational variations. This capability can significantly reduce the dependency on manual parameter tuning and enhance performance under dynamic conditions (Refaat et al., 2020).

Discussion and conclusion

A photovoltaic (PV) power system is employed to extract maximum available power through an appropriate power-matching mechanism. In this process, any portion of unextracted power from the solar module is dissipated as surface heat, underscoring the importance of effective maximum power point tracking (MPPT). The proposed Simulink model demonstrates strong performance, particularly for autonomous WSN nodes, where the fuzzy logic–based MPPT controller achieves its highest efficiency under elevated irradiance conditions.

Comprehensive modeling, simulation, and experimentation were conducted for Solar Energy Harvesting Wireless Sensor Nodes (SEH-WSNs). Using MATLAB/Simulink (R2023a), two MPPT strategies—the conventional perturb and observe (P&O) method and the fuzzy logic–based controller—were evaluated within the solar energy harvester system.

The results confirm that the fuzzy logic MPPT controller consistently outperforms the P&O algorithm. Comparative simulation data show that the fuzzy-based MPPT yields higher efficiency, enhanced power extraction and reduced oscillations around the maximum power point relative to the conventional controller. Thus, the fuzzy logic–based solar energy harvester system exhibits superior overall performance.

Future research may extend this work by integrating more advanced MPPT techniques such as neural networks and machine learning models, as well as optimization algorithms including particle swarm optimization, dragonfly optimization, and genetic algorithms, which have shown strong potential in previous studies (Al-Gizi et al., 2017; Yap et al., 2020; Kanaujia et al., 2024).

Conflict of interest

The author(s) of this research state that there is no conflict of interest in the publication of this paper.

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